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Pressure-Compensating System for Gas-Filled Transducers

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ABSTRACT

A self-contained pressure-compensating system has been developed for use with the USRD type J11 moving-coil transducer at ocean depths to 600 ft. This system conserves compensating gas for uninterrupted use over a period of 8 hours or more. It responds to changes in depth by holding the pressure differential on the diaphragm of the transducer to less than 0.7 psi with negligible effect on the acoustic response.

PROBLEM STATUS

This is an interim report on the problem.

PROBLEM AUTHORIZATION

NRL Problem S02-31

Project RF 05-111-401-4472

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PRESSURE-COMPENSATING SYSTEM FOR GAS-FILLED TRANSDUCERS

INTRODUCTION

In recent years, it has become highly desirable to operate several types of gas-filled moving coil transducers [1] at depths much greater than that for which they were originally designed. To provide this capability for the USRD type J11 transducer and similar types, a self-contained pressure-compensating system (SCPCS) has been developed. The new system extends the operating depth to 600 ft and permits operation for eight hours or longer without replenishment of the compensating gas supply.

Operation of the moving-coil element of the type J11 transducer requires that the gas pressure at the back of the vibrating diaphragm be equal to the hydrostatic pressure at its front. This requirement is satisfied in the standard USRD type J11 transducer at the depths for which it was designed by sealing the rear of the chamber occupied by the diaphragm and moving-coil assembly with a gas-filled butyl-rubber bladder that is exposed to the external water pressure at the rear of the transducer housing. As the hydrostatic pressure increases with depth, the gas volume in the flexible bladder is reduced, and the internal pressure increases in inverse proportion. This arrangement can compensate for pressure only to the 80-ft depth.

The new SCPC system, an improvement over an earlier deep-submergence compensating system [2], is enclosed in the transducer housing between the chamber that contains the moving-coil assembly and a chamber that contains the rubber bladder. The additional gas supply is contained in a high-pressure gas bottle which, together with a regulator, is strapped to the transducer housing as shown in Fig. 1. The rubber bladder has been retained to provide compensation for small variations in operating depth without drawing gas from the supply bottle.

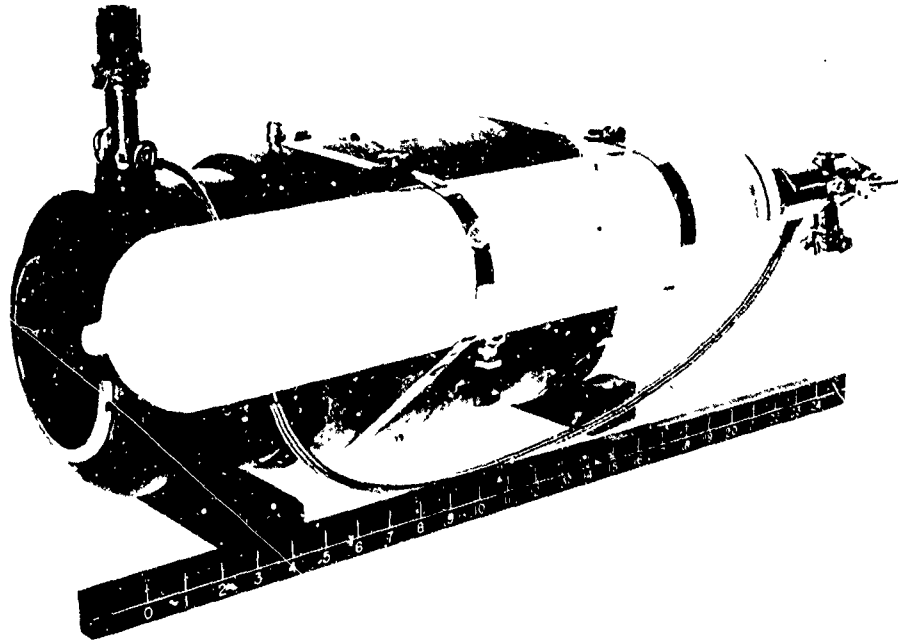


Fig. 1. Self-contained pressure-compensating system attached to USRD type J11 transducer.

SPECIFICATIONS

The following requirements were established for the design of the SCPCS for deep submergence:

1. Depth capability: 600 ft.
2. Conservation of compensating gas for moderate change in depth (for example, in rough seas or while being towed) to allow for extended use.
3. Maximum static pressure differential on transducer diaphragm: 0.7 psi.
4. Negligible change in transducer response characteristics with depth.

DESIGN AND CONSTRUCTION

To satisfy the depth and size requirements of the system, a 183-in.³ high-pressure, stainless-steel bottle rated at 1800 psig was chosen as the supply tank for the compensating gas.

To meet the requirement for length of submergence, the system was designed to compensate for minor change in depth without drawing gas

continuously from the storage bottle. Compensation for the pressure change on descent to and ascent from the operating depth is provided by a high-pressure, 2-stage, regulated gas supply system and a low-pressure differential relief valve. This system feeds the rubber bladder that compensates for pressure changes such as those caused by surface waves and ship's motion. A diagram of the flow system is shown in Fig. 2. Figure 3 shows the bladder attached to its mounting ring.

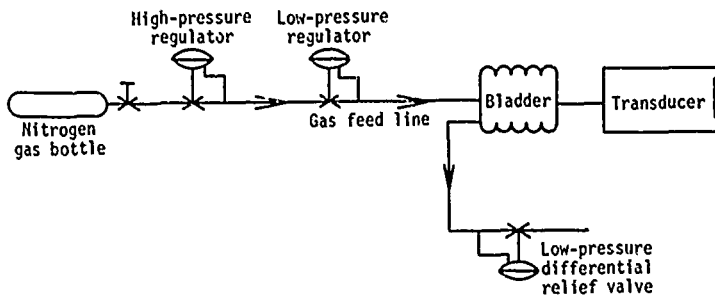


Fig. 2. Flow of gas in the system.

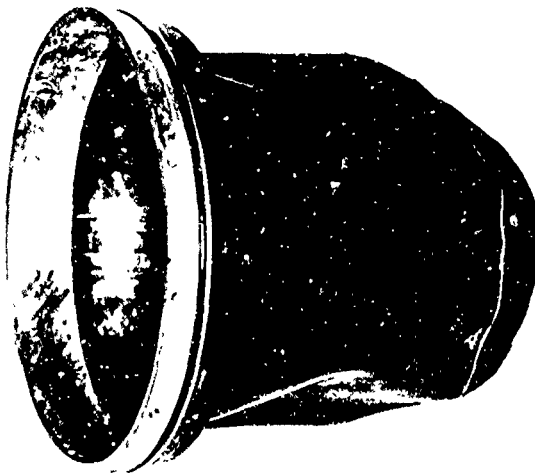
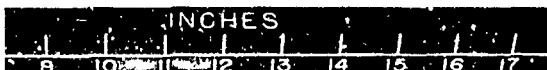


Fig. 3. Rubber compensating bladder and mounting ring.



Other details of the SCPCS are shown in Figs. 4 and 5. The chamber containing the rubber bladder (right, Fig. 5) is separated from the chamber containing the moving-coil assembly (left) by two bulkhead plates that enclose a thin free-flooding chamber (4). Compensating pressure is transmitted from the bladder chamber to the moving-coil chamber through holes in four bolts (9) and an acoustic resistor. Several holes in the transducer housing admit external water pressure to the flooded chamber between the two bulkhead plates and thus to the diaphragm (2) that operates the Schrader valve (5).

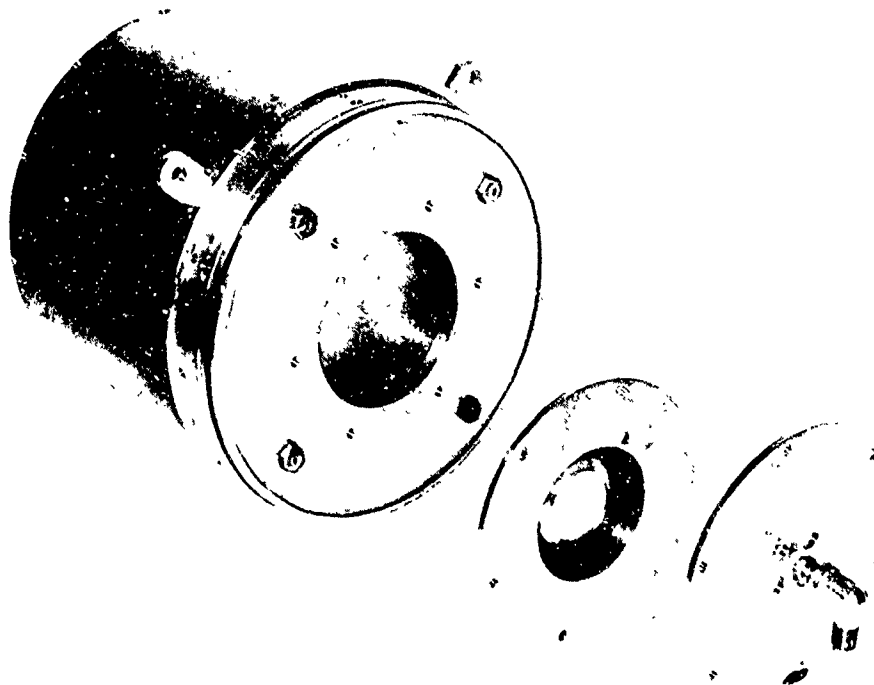


Fig. 4. Bladder housing (left) and low-pressure-regulator components (right and center).

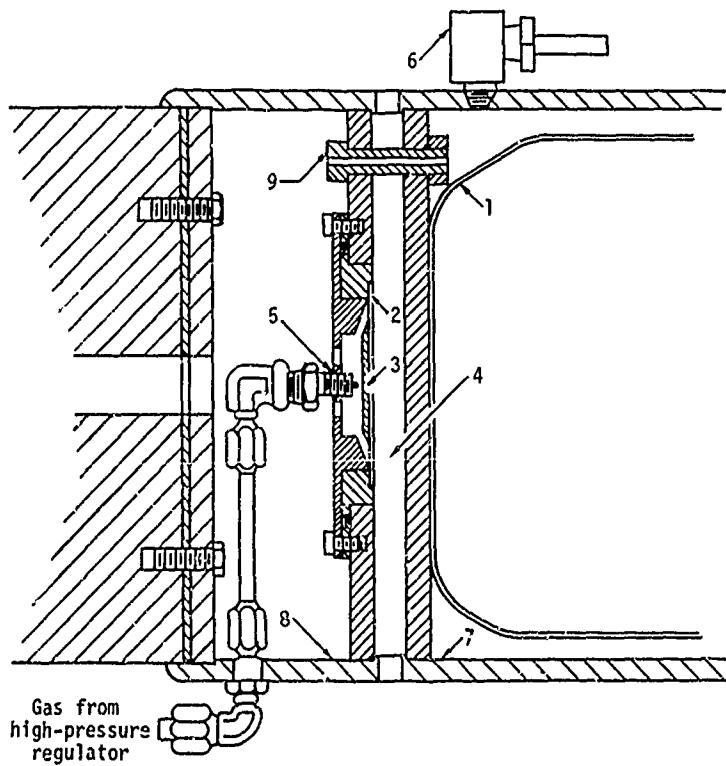


Fig. 5. Details, low-pressure regulator.

OPERATION

High-pressure dry nitrogen is fed through a hand-operated SCUBA "K" valve to the first-stage (high-pressure) regulator (Healthways "Scuba Star" model), which maintains a downstream gas pressure 80 psi above the ambient hydrostatic pressure. These components are shown attached to the high-pressure gas-supply bottle in Fig. 1. This pressure-regulated gas is delivered through a flexible hose to the second-stage, or low-pressure regulator, which is built into the forward bulkhead of the SCPCS as shown in Figs. 4 and 5.

The low-pressure regulator delivers compensating gas to the transducer in the following manner (Fig. 5): When the transducer has been lowered to the limit of depth compensation by the rubber bladder (1), the neoprene diaphragm (2) and the attached brass plate (3) are pushed by the positive differential pressure in the flooded chamber (4) against the stem of a Schrader valve (5), which releases gas delivered from the high-pressure regulator to the chamber that contains the moving-coil assembly. Gas is released until the differential between the internal gas pressure of the transducer and the external hydrostatic pressure is reduced and the rubber diaphragm returns to a neutral position. When the compensation limit of the rubber bladder has been reached on ascent, the low-pressure differential relief valve (6) releases gas from the system, reducing the internal gas pressure as the external hydrostatic pressure decreases. An external view of the low-pressure regulator assembly and relief valve is shown in Fig. 6.

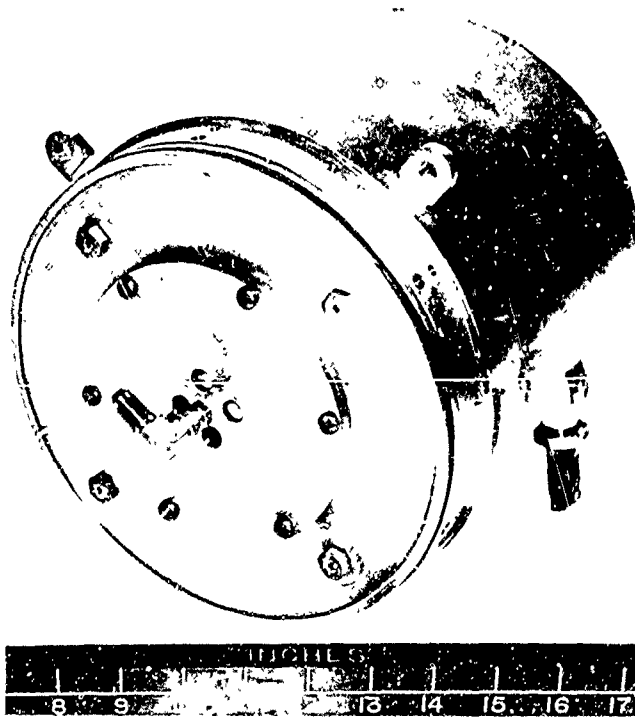


Fig. 6. Low-pressure regulator and relief valve, assembled.

To limit the pressure differential on the transducer diaphragm so that structural failure will not occur, the low-pressure regulator and the low-pressure differential relief valve are set to operate at 0.4 and 0.7 psi, respectively.

THEORY

Two factors that affect the change of acoustical response with depth are (1) the effective stiffness of the transducer element, the attached housing, and the enclosed bladder, and (2) the first resonance frequency of the system. These can be approximated by the equations for a Helmholtz resonator [3]:

$$s_c = \rho_0^2 S/V, \quad (1)$$

$$f_0 = (c/2\pi) (S/\ell'V)^{1/2}, \quad (2)$$

where s_c is the stiffness of the vibrating system, ρ_0 is the density of the compensating gas, c is the speed of sound in the gas, S is the cross-sectional area of the transducer diaphragm, V is the total volume of the enclosed system, f_0 is the first resonance frequency of the Helmholtz resonator, and ℓ' is the effective length of the opening in the resonator.

It can be seen from Eqs. (1) and (2) that the stiffness and the resonance frequency are inversely proportional to the volume of the enclosed gas. This volume changes with depth as the volume within the rubber bladder varies.

The effect of the changing volume of the bladder is minimized by the air passages through the four bolts (No. 9, Fig. 5) that join the two bulkhead plates. As described in Appendix A, these small passages act as an acoustical filter above 16 Hz and thus isolate the transducer, whose vibrating system resonates at 50 Hz, from the change in volume of the bladder.

A peak produced in the response at 200 Hz by acoustical resonance in the 7/8-in.-dia passage at the center of the transducer element has been reduced by installing an acoustic resistor at the rear of this passage as shown at the right in Fig. 7. Figure 7 (left) also shows the 3/4-in.-thick plate at the rear of the bladder housing that serves as an infinite-baffle enclosure and flattens the acoustic response at the resonance frequency of the transducer.

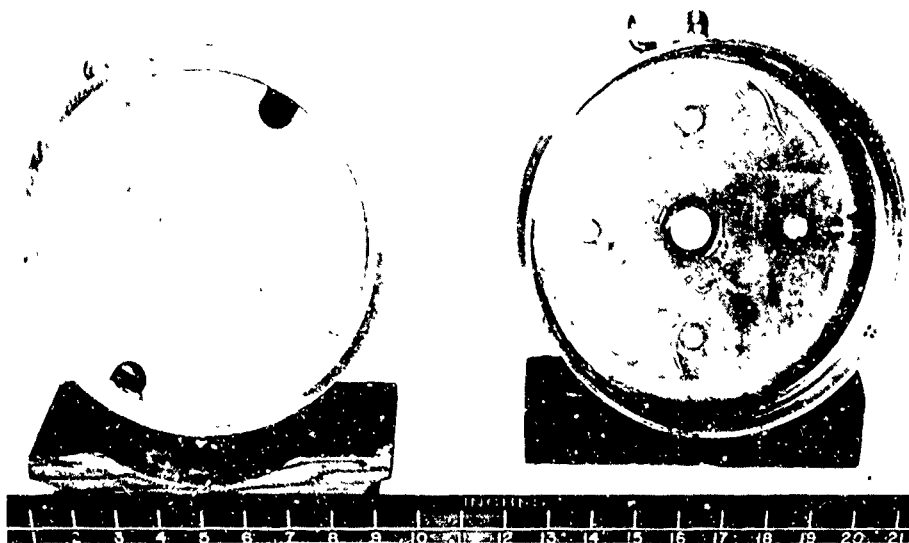


Fig. 7. Left: rear plate of transducer housing;
right: housing for transducer element, with
acoustic resistor in center.

OPERATING CHARACTERISTICS

Acoustic Response

Seven successful tests of the SCPCS have been carried out in a 30-gal tank at hydrostatic pressure to 267 psig, which is equivalent to the water depth 600 ft. Acoustical tests have been made to 172 ft. Figure 8 shows the transmitting current response at two depths for the J11 with its pressure-compensating system. The maximum variation of response with depth on ascent and descent (varying volume of the compensation bladder) is 2 dB in the frequency range 50 Hz to 10 kHz. The nominal value of the response is 55 dB re 1 μ bar/A in the range 50 Hz to 6 kHz. The acoustic resistor adequately reduces the 200-Hz resonance of the passage to the transducer element.

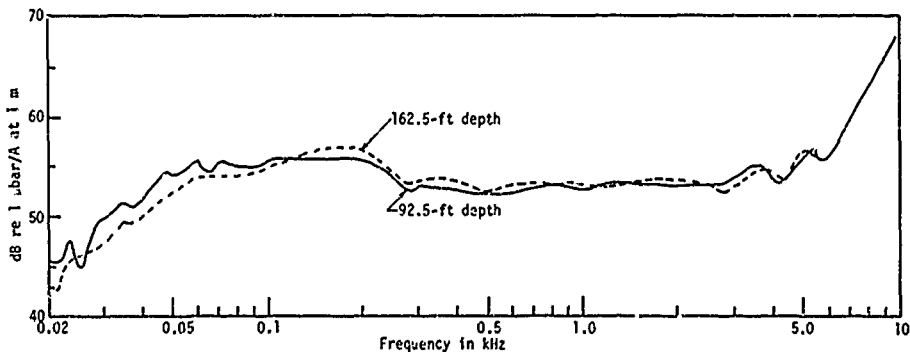


Fig. 8. Transmitting current response, USRD type J11
transducer with nitrogen-filled, self-contained
pressure-compensating system.

By removing the rear plate of the bladder housing, substituting an open grille, and using helium as the compensating gas, it is possible to attain the transmitting current response 65 dB re 1 μ bar/A at 47 Hz.

Conservation of Compensating Gas

Several tests were carried out to determine the amount of depth change that can be compensated by the rubber bladder alone. At the maximum depth 600 ft, the rubber bladder will provide compensation for a decrease in depth of 378 ft. The amount of compensation by the bladder is reduced with decrease in operating depth as shown in Fig. 9.

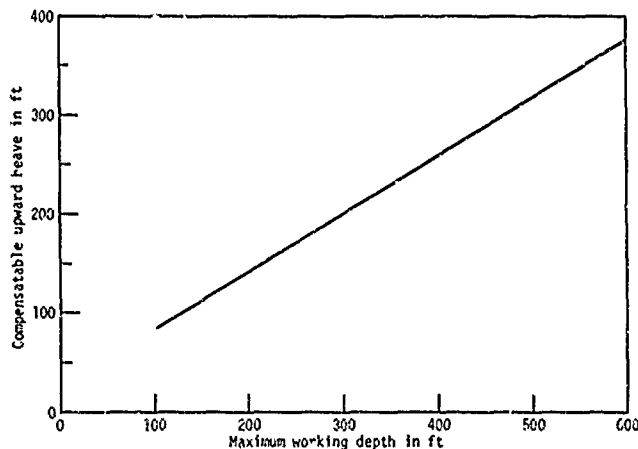


Fig. 9. Relation of compensatable upward heave to maximum working depth.

Calculations in Appendix B show that if the SCPCS gas supply is fully charged to start with, seven excursions can be made from the surface to 600 ft and back before it becomes necessary to replenish the gas supply. The amount of gas used from the bottle for each full depth excursion is based on the drop in bottle pressure recorded during tests in the pressure tank. Because of charging limitations, the highest gas-bottle pressure attainable during the tests was 1480 psig.

Maximum Pressure Differential

The maximum pressure differential that occurred within the transducer was not measured. The maximum value would occur during rapid descent to or ascent from operating depth, when the highest demands are made on the supply regulators and the relief valve. Maximum rates of descent and ascent during the tests were recorded, however. The highest rate of descent was 8.29 ft/sec; the highest ascent rate, 9.21 ft/sec. These rates were experienced without structural failure of the transducer.

CONCLUSION

This self-contained pressure-compensating system adequately replenishes compensating gas for the USRD type J11 transducer during a long period of submergence with little effect on the mechanical and acoustical operation of the transducer. Further development will be carried out to adapt the system for use with the USPD moving-coil transducers types J9 and J13.

References

1. C. C. Sims, "High-Fidelity Underwater Sound Transducers," Proc. IRE 47, 866-871 (1959).
2. T. A. Henriquez, "Air-Compensated Audio Transducers for Operation to 500-Foot Depth," Navy Underwater Sound Reference Laboratory Research Report No. 80 (1966)[AD-627 383].
3. L. E. Kinsler and A. R. Frey, Fundamentals of Acoustics (John Wiley and Sons, New York, 1962), 2nd ed., pp. 187, 193.

Appendix A

ATTENUATION OF SOUND BETWEEN HOUSING OF TRANSDUCER ELEMENT AND BLADDER HOUSING

Figure A1 shows the acoustical system considered in determining the sound transmission through the 2.54-mm-dia (0.100 in.) holes through the centers of the four bulkhead bolts leading from the housing of the transducer element to the bladder housing.

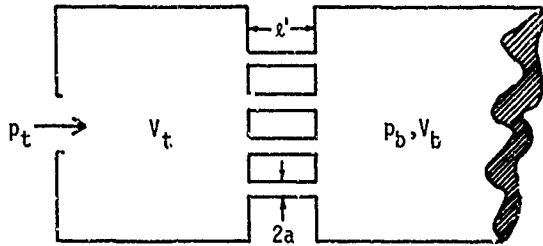


Fig. A1. Acoustical path between bladder housing and that of transducer element; V_t is volume of element housing; V_b is volume of bladder housing; a is radius and l' the length of hole in each bolt.

Figure A2 shows the equivalent electrical circuit for this acoustical system. The elements C_t and C_b of the circuit are the volume compliances of volumes V_t and V_b , respectively, where $C_t = V_t/\rho_0 c^2$ and $C_b = V_b/\rho_0 c^2$; ρ_0 is the density of, and c is the sound speed in, the compensating gas; p_t and p_b are the sound pressures at the entrance to the transducer housing and the bladder housing, respectively.

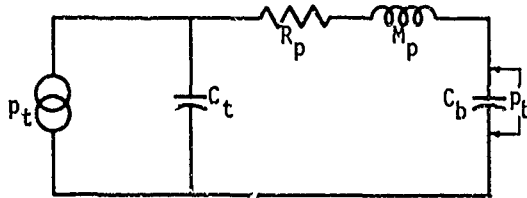


Fig. A2. Equivalent electrical circuit for acoustical path shown in Fig. A1.

For the boundary condition $16 \text{ Hz} < f < 3900 \text{ Hz}$, the total acoustical resistance $[A1]$ of the four passages is

$$R_p = \rho_0 (1/4\pi a^2) (2\omega\mu)^{1/2} (2 + l'/a),$$

and the acoustical inductance is

$$M_p = \rho_0 (l' + 2l'')/4\pi a^2,$$

where $\omega = 2\pi f$, μ is the kinematic coefficient of viscosity of the compensating gas, and $l'' = 0.85a$ is the end correction for the passage.

Applying network analysis to the equivalent electrical circuit, we find that

$$p_b/p_t = 1/[(1 - \omega^2 C_b M_p/4) + j(\omega C_b R_p/4)].$$

Numerical values for the worst condition (V_b maximum) and nitrogen gas are: $V_b = 0.00420 \text{ m}^3$, $a = 0.00127 \text{ m}$, $l' = 0.0476 \text{ m}$, $c = 343 \text{ m/sec}$, and $\mu = 1.56 \times 10^{-5}$. With these values, we get

$$p_b/p_t = 1/[(1 - 8.75 \times 10^{-5} \omega^2)^2 + (3.89 \times 10^{-4} \omega^{3/2})^2]^{1/2}.$$

For specific frequencies, the attenuation is:

Freq (Hz)	20 log (p_b/p_t) (dB)
50	-19
100	-34
3900	-127

Reference

- A1. L. L. Beranek, Acoustics (McGraw-Hill Book Co., Inc., New York, 1954), pp. 137-138.

Appendix B

EXPENDITURE OF HIGH-PRESSURE GAS

To supply compensating gas to the low-pressure regulator at the depth 600 ft, the gas bottle pressure must be at least 347 psig, where the pressure gradient in seawater is 0.445 psi/ft and the pressure supplied to the low-pressure regulator is to be maintained at 80 psi above the hydrostatic pressure.

The total mass of compensating gas available from the high-pressure gas bottle before its initial pressure p_1 is reduced to the final allowable pressure p_2 is

$$m_t = V_g (\rho_1 - \rho_2),$$

where V_g is the volume of the gas bottle and ρ_1 and ρ_2 are the initial and final gas densities at pressures p_1 and p_2 , respectively.

From the general law for perfect gases, $\rho_1 = p_1/RT$ and $\rho_2 = p_2/RT$, where T is absolute temperature and R is a constant depending on the units used. Then,

$$m_t = V_g (p_1 - p_2) RT;$$

but similarly, the mass of gas expended in one excursion from surface to the depth 600 ft is

$$m_e = V_g \Delta p / RT,$$

where Δp is the reduction in pressure of the gas in the storage bottle and, from measurement, is equal to 200 psi.

Then the number of excursions to 600 ft that can be made without replenishing the gas bottle is $m_t/m_e = (p_1 - p_2)/\Delta p$.

For the given conditions, p_1 is 1800 psig, p_2 is 347 psig, and m_t/m_e is approximately equal to seven excursions.

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Gas-filled transducers						
USRD type J11 transducer						
Moving-coil transducers						
Differential pressure						